



FLOW VISUALIZATION OF AIRCRAFT IN FLIGHT BY MEANS OF BACKGROUND ORIENTED SCHLIEREN USING CELESTIAL OBJECTS

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OUTLINE

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- BOSCO Concept
 - Background Oriented Schlieren
 - Imaging system
 - Test operation concepts
- Flight Tests
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 - BOSCO Phase I (2016)
 - BOSCO Phase II (2017)
- Future Work

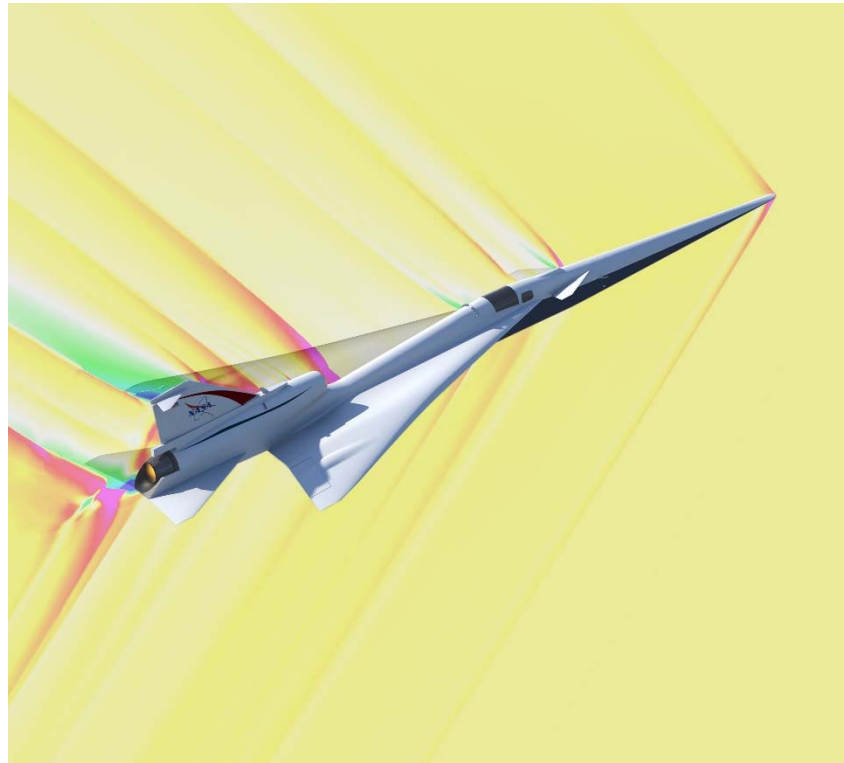




MOTIVATION

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- NASA Commercial Supersonic Technology
 - Desire for a schlieren system for full scale aircraft in flight to visualize shockwaves generated by supersonic aircraft
 - Validate/refine shock modeling for low boom airframe design



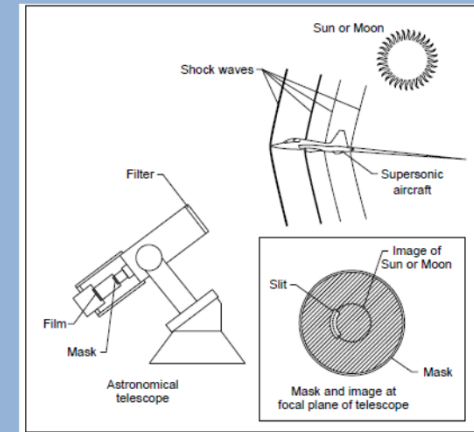
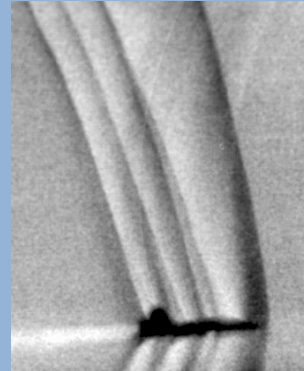


BACKGROUND - EXISTING FULL SCALE SCHLIEREN SYSTEMS

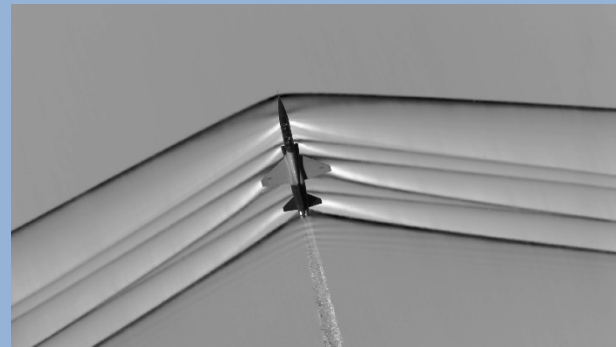
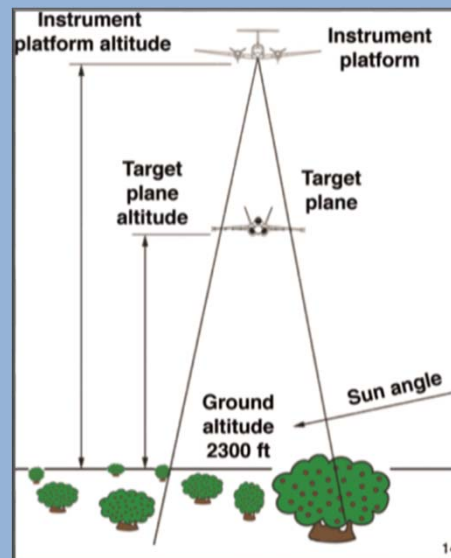
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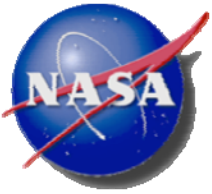
Ground to air solar edge schlieren

- Schlieren for Aircraft in Flight (SAF)
 - NASA, Weinstein 1993
- Ground to Air Schlieren Photography System (GASPS)
 - Digital equivalent of SAF, Metrolaser Inc.



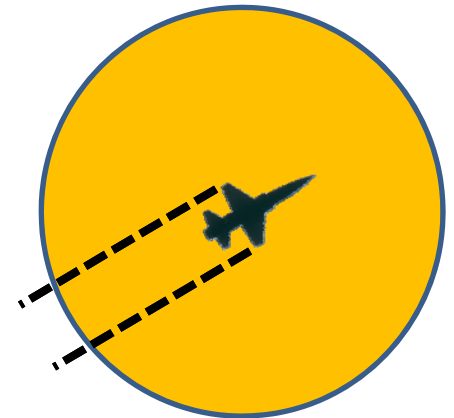
Air to Air Background Oriented Schlieren (AirBOS) NASA, Heineck, Banks. 2015

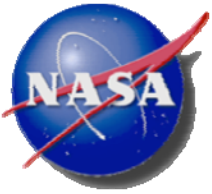




Gaps in capability for existing systems

- SAF (Ground to air solar edge)
 - Flow features roughly orthogonal to the solar limb are not imaged. Not a fully 2-D map of air density gradients
 - Resolution of the system is tied to camera frame rate. Increasing the sensor size requires a proportional increase in frame rate. Hardware has an inverse relationship.
- AirBOS
 - Images are mainly plan-form. Aggressive maneuvering is required for side views.
 - Camera aircraft must fly higher altitude than aircraft to be imaged. (low boom demonstrator to fly > 50kft)

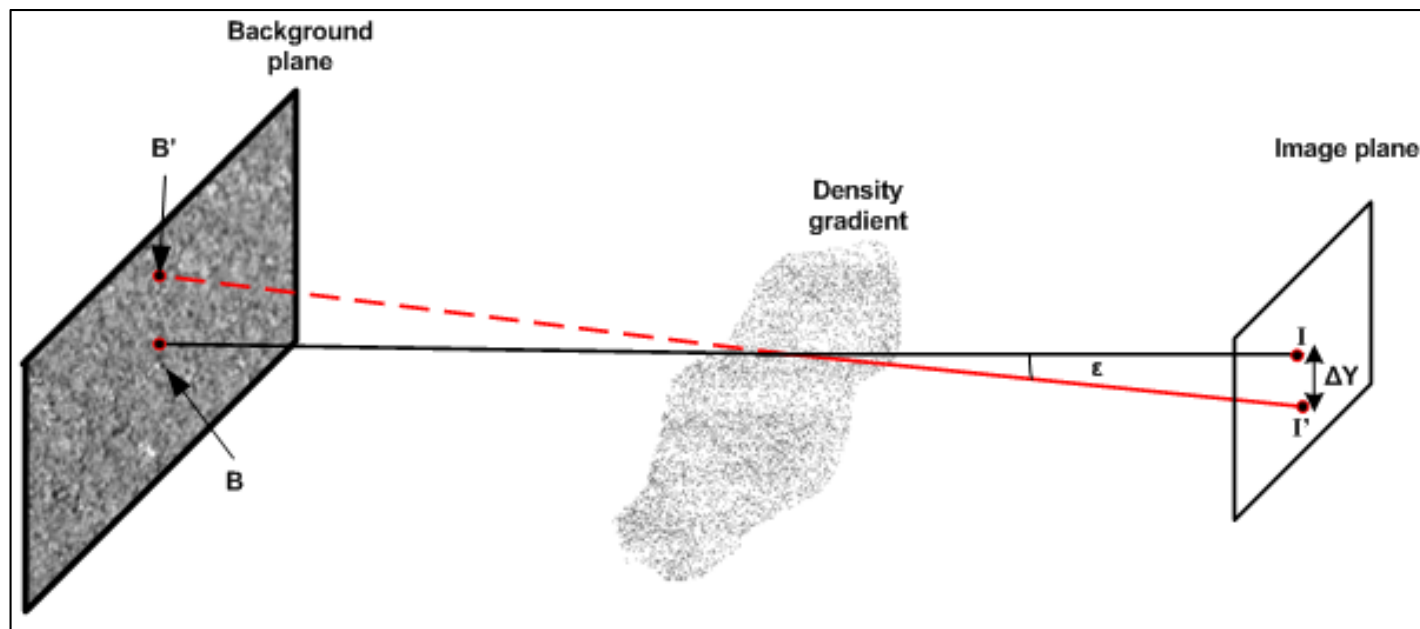




BACKGROUND ORIENTED SCHLIEREN CONCEPT

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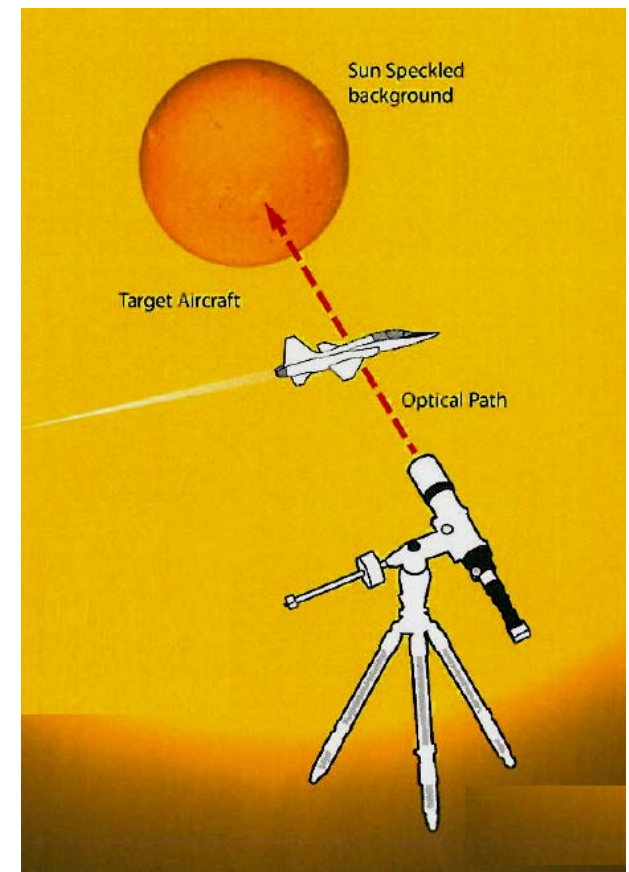
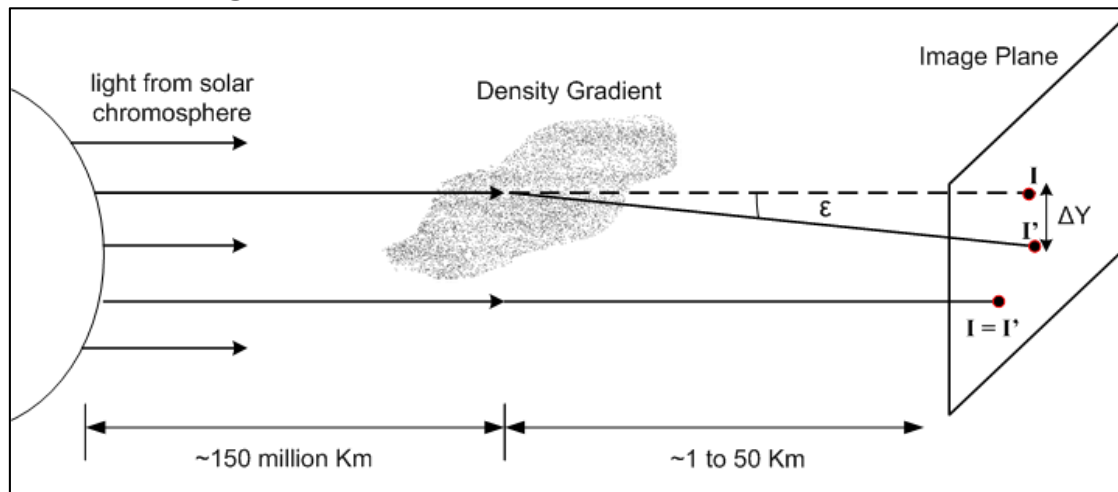
- Visualizes light ray deflections by calculating movement of features in a background
- Provides a full 2-D measurement proportional to the gradient of air density
 - With no density gradient, a ray from B will be imaged at point I
 - With a density gradient, a ray from B will be imaged at I', making it appear it is at point B'
 - Finding the difference in location of B and B' gives a measure of ray deflection and therefore density gradient





Background Oriented Schlieren using Celestial Objects (BOSCO)

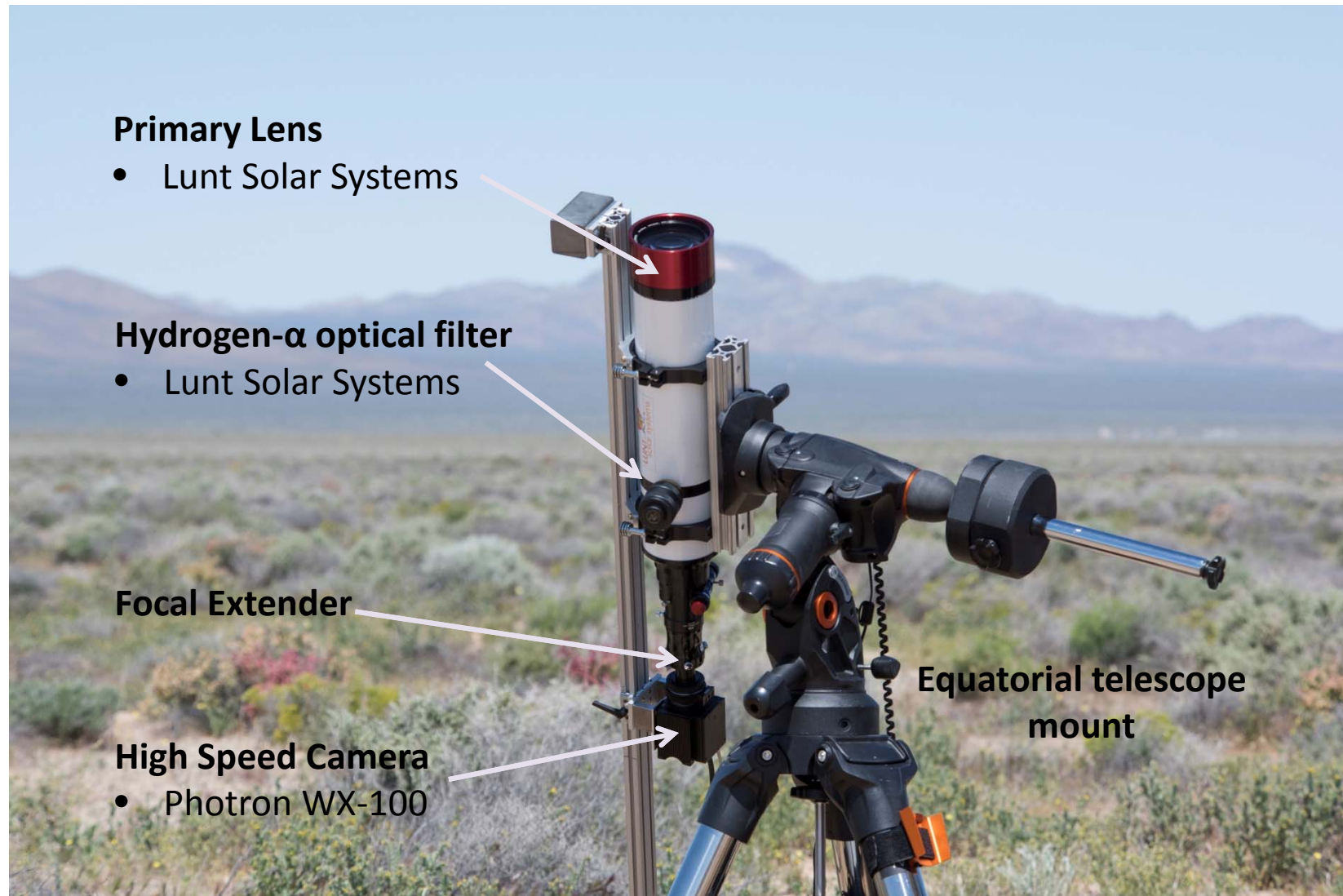
- Uses narrow band optical filters to give the sun a textured appearance. The texture allows for the BOS method
- Advantages:
 - Full 2D measurement of a BOS system
 - Ability to image from below and to the side of the target aircraft





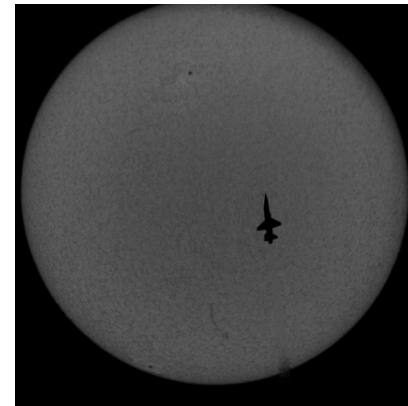
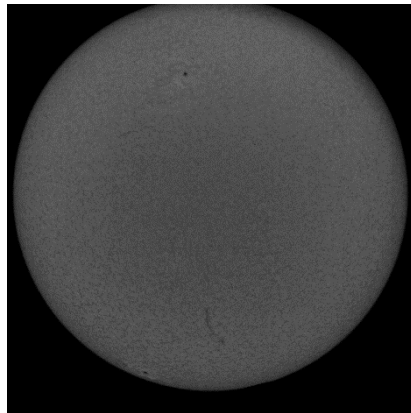
BOSCO – IMAGING INSTRUMENTATION

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- Optical Flow
 - Developed for computer vision applications in the 1970's/80's
 - Uses the “brightness constancy criterion” – brightness is constant between 2 image pairs, differences in brightness correspond to motion
 - Outputs “flow” vectors, 2D solutions of pixel displacement

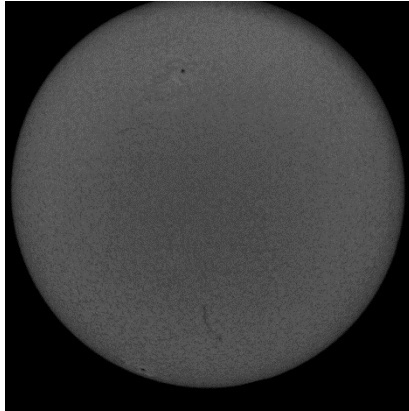




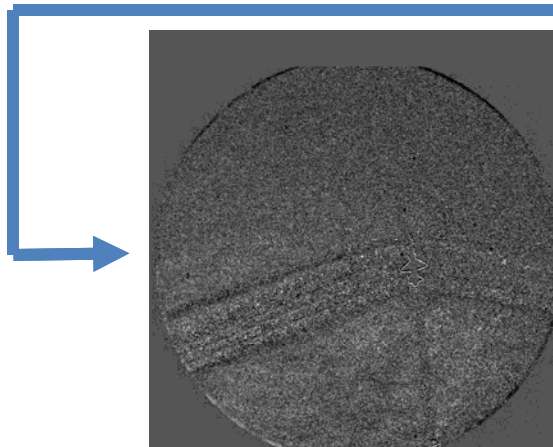
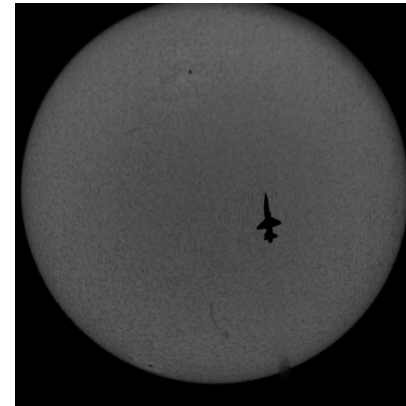
BOSCO – IMAGE PROCESSING

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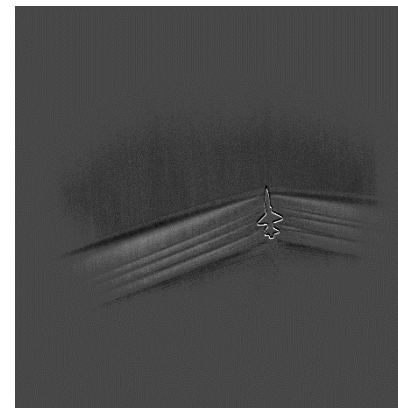
A frame before the aircraft eclipses is used for the reference background



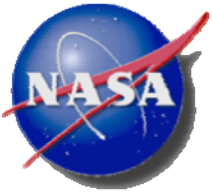
Each eclipse frame is aligned with the background frame



Optical Flow is performed on the image pair resulting in a magnitude of pixel displacements



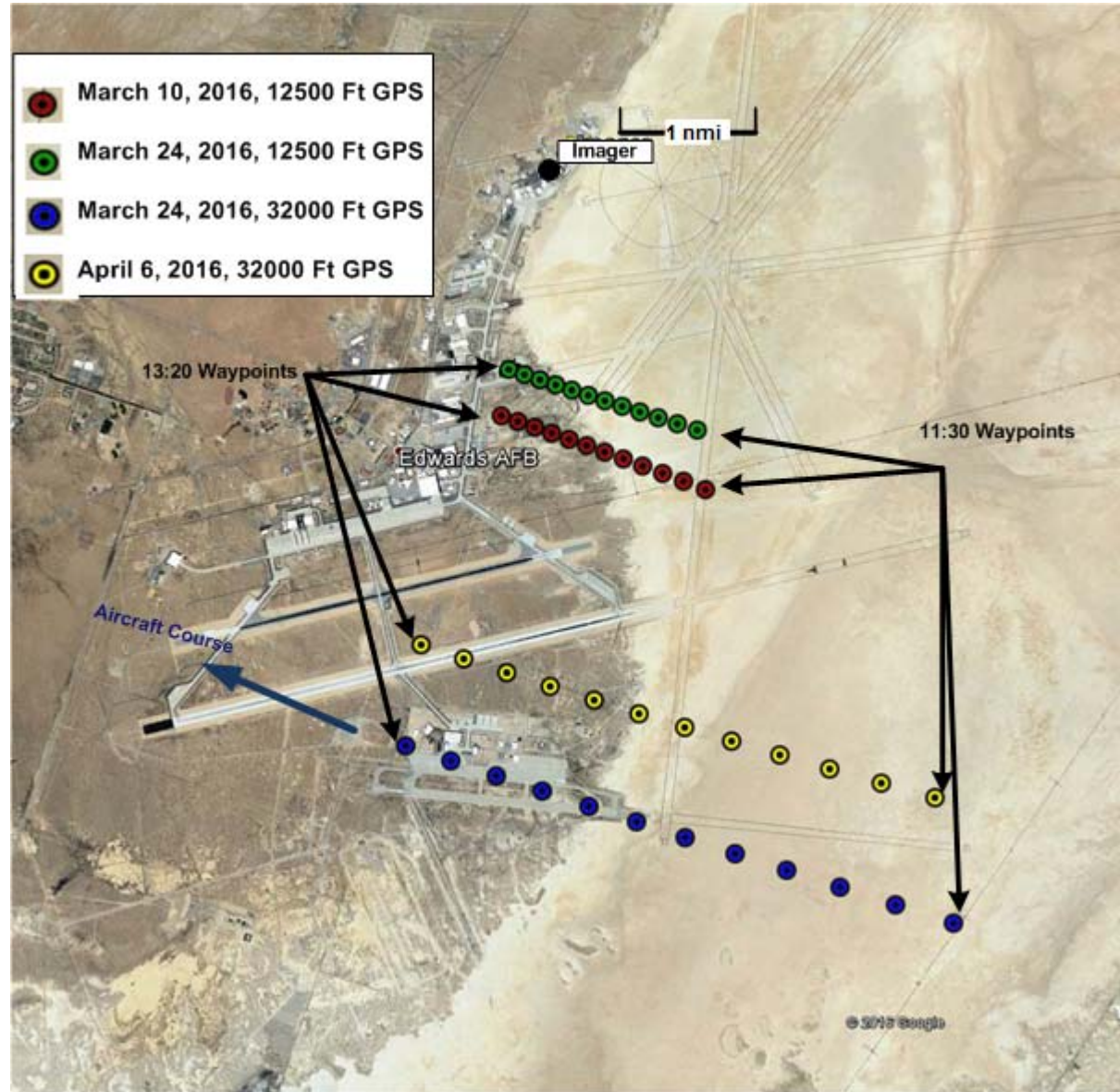
This is repeated for all frames in the eclipse. The median of all the results of all the frames is taken, resulting in the final de-noised schlieren image



BOSCO - TEST OPERATIONS

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- Aircraft waypoints were calculated based on time of eclipse, ground position of the imager, and desired altitude of the aircraft.
- Course of the aircraft followed the sun direction across the sky, and flights occurred near the maximum solar elevation angle, to minimize the need for accurate waypoint timing.
- Range from the imager to the aircraft increases as sun elevation decreases and as altitude difference between the imager and aircraft increases



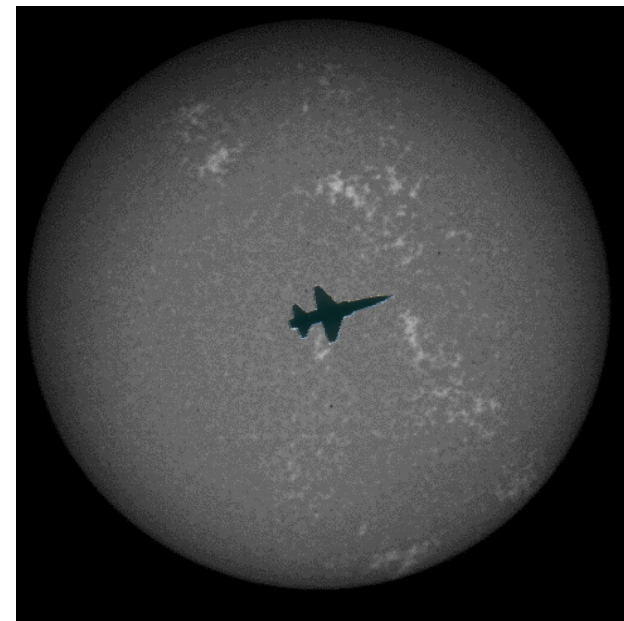
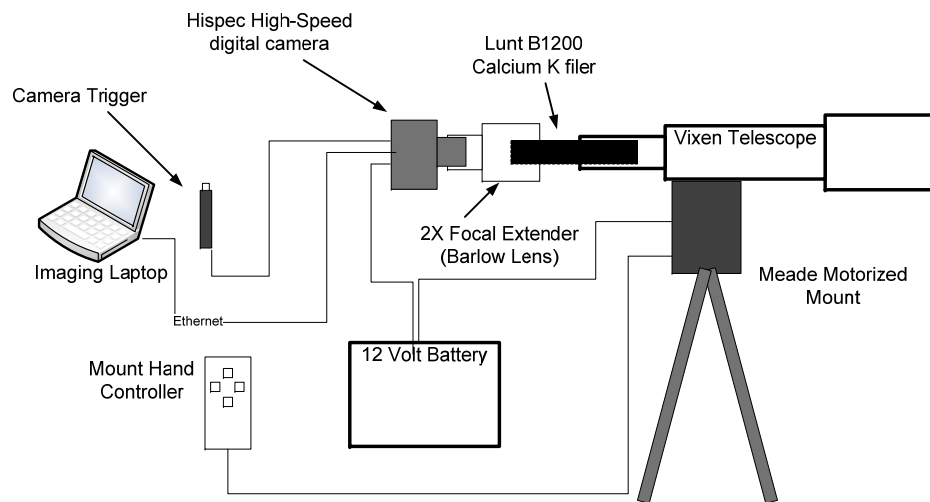


- Calcium K Eclipse Background Oriented Schlieren (CAKEBOS)
 - Proof of Concept April 2015
- BOSCO – phase I
 - Tested Improvements in the imaging system. April 2016
- BOSCO – phase II
 - Tested new compact imaging system. April 2017



Calcium-K Eclipse Background Oriented Schlieren (CaKEBOS) April 2015

- Proof of concept test
 - Objective: Demonstrate the feasibility of using Background Oriented Schlieren (BOS) technique in a ground to air system.
 - Used non-optimized hardware already acquired for a previous test
 - Calcium K optical filter

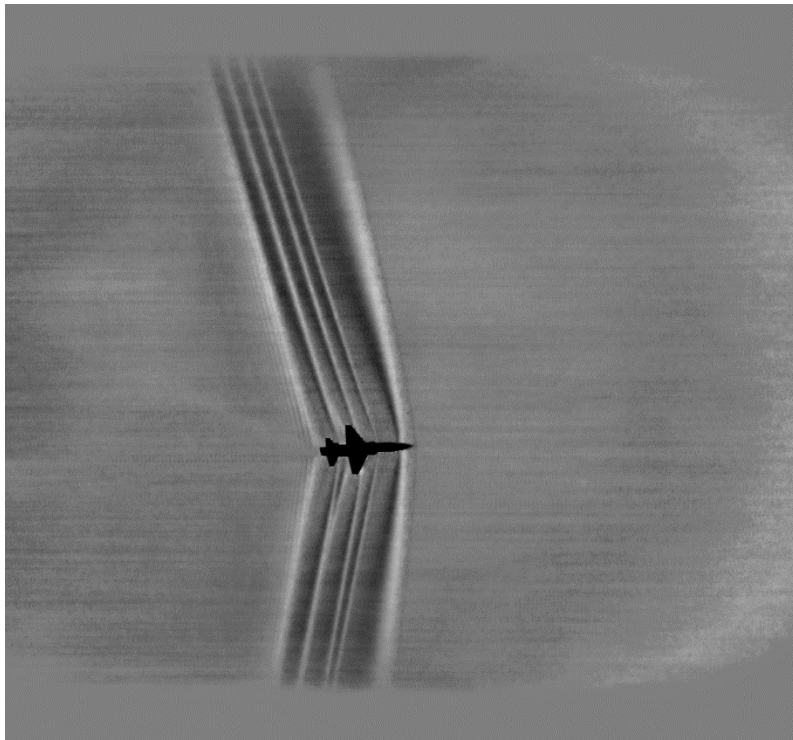




FLIGHT TESTS - CAKEBOS

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- Resulting images greatly exceeded expectations
 - System was limited by the digital resolution



Horizontal density gradient



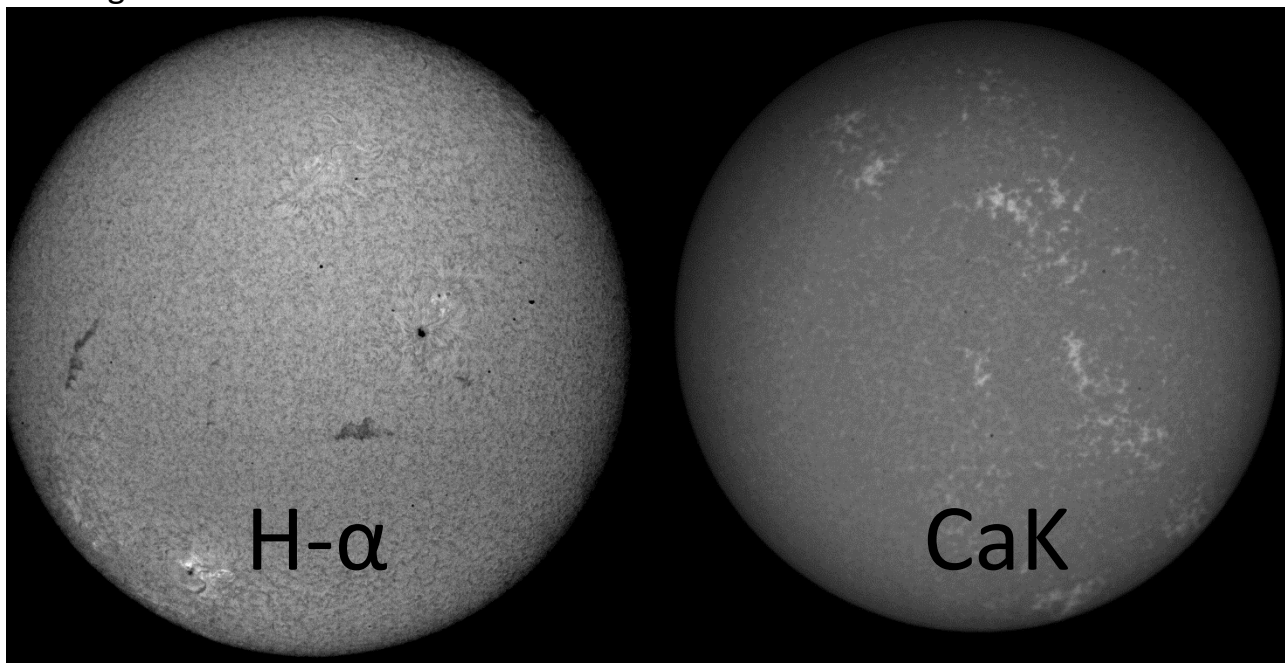
Vertical density gradient

T-38 30000ft AGL, 6.5 mile range, Mach 1.05



BOSCO – Phase I, April 2016

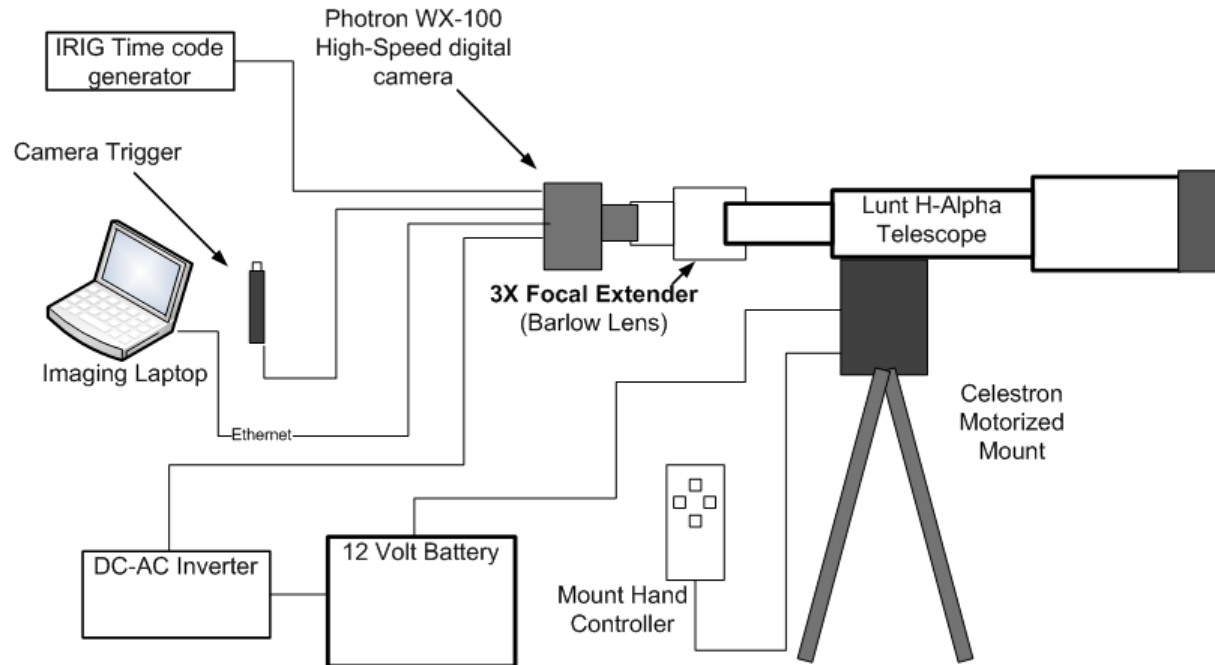
- Success of CaKEBOS allowed for equipment upgrades
 - Higher resolution Camera
 - Photron WX-100: 2048 X 2048 pixels @ 1000 frames/sec
 - Hydrogen alpha telescope
 - More uniform texture distribution
 - Speckle size is smaller and therefore better for BOS
 - Higher contrast





BOSCO SYSTEM (H-A)

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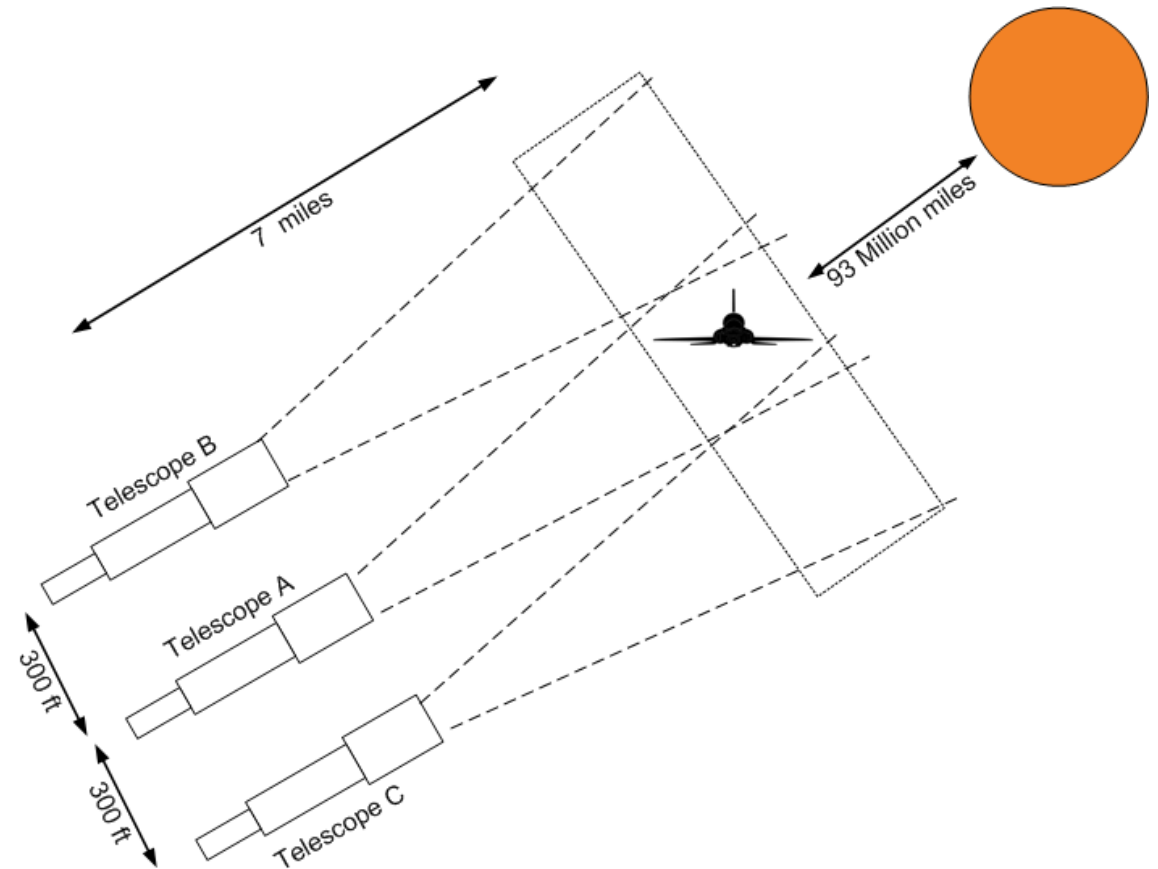


- 100 mm f/7 refractor telescope
- H Alpha filter
- 3x Focal extender – Effective focal length: 2100 mm
- Photron WX-100
 - 2048 X 2048 pixels
 - 1000 frames/sec
 - 333 μ s integration time
- Manual solar tracking
- Manually triggered at pilot's "mark" call or visual eclipse



BOSCO – 3 IMAGER ARRAY

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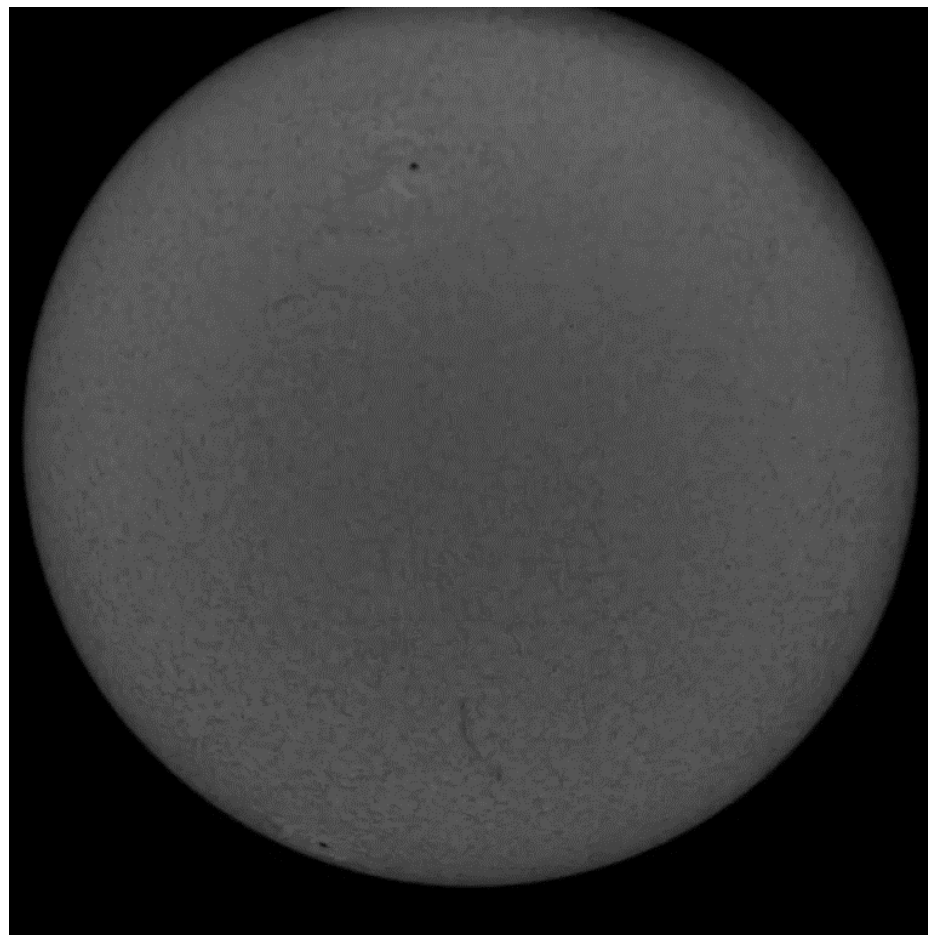


To increase the field of view of the system, 3 imagers were used in a spaced array in the direction perpendicular to the aircraft course



BOSCO- PHASE I RAW DATA

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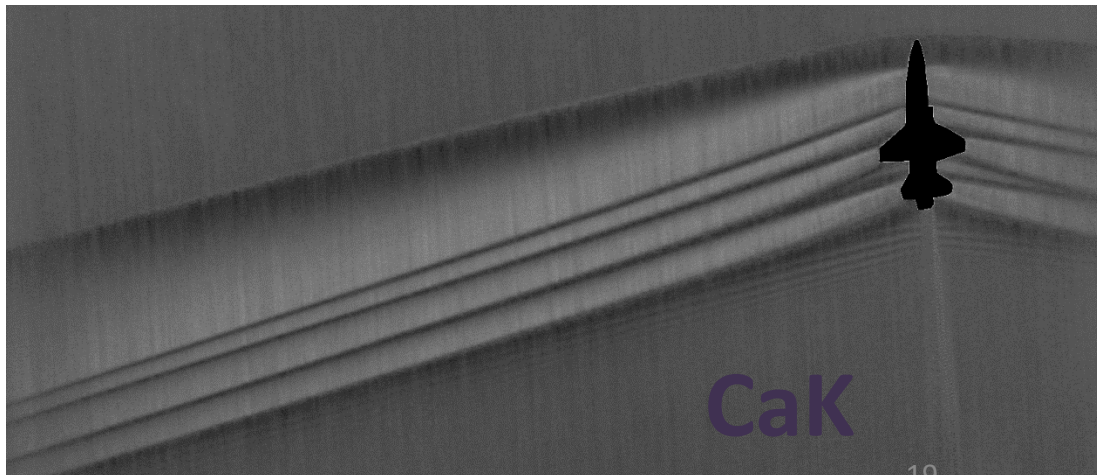
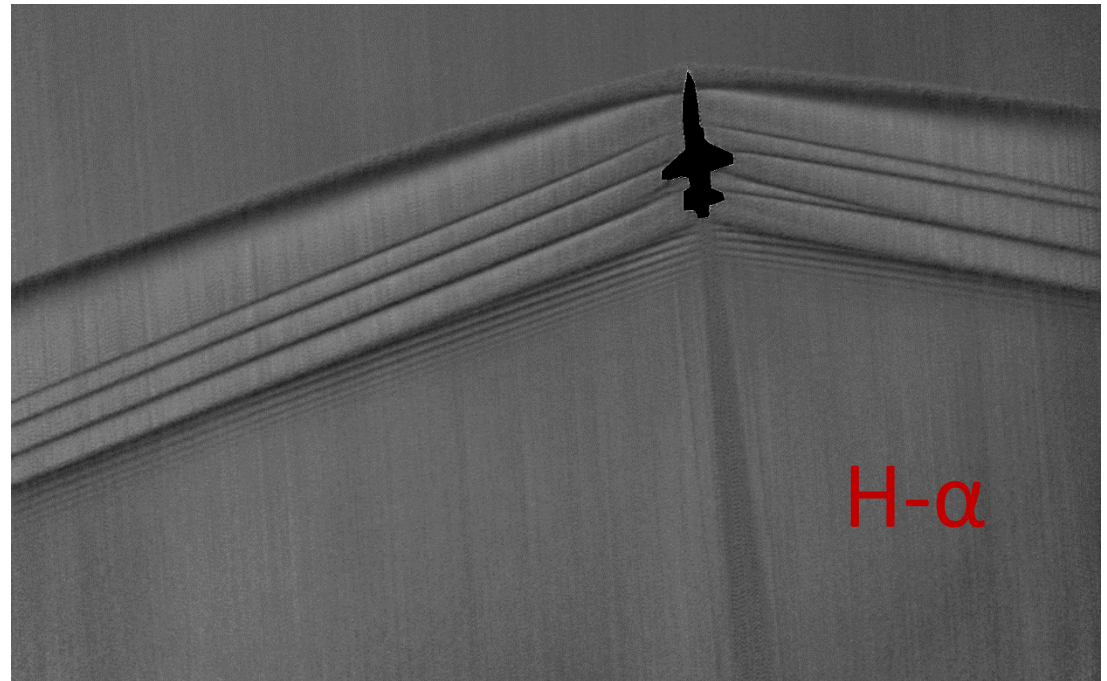




BOSCO RESULTS

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- Imager design improvements verified in BOSCO – Phase I
 - H- α filter provides a better background than CaK
 - Higher digital resolution provided better schlieren image resolution
 - Higher frame rate gave more eclipse frames for improved de-noising

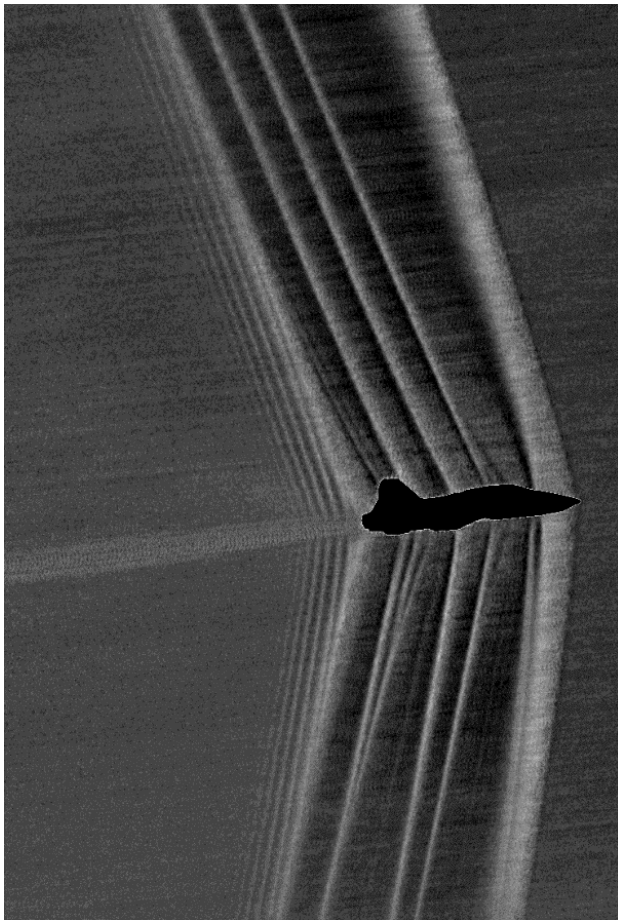




BOSCO-PHASE I RESULTS

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- Aircraft banked at sun elevation angle for direct side view
 - Direct side view is of most interest for eventual imaging of low boom demonstrator



3 Image, wide field of view

The top and bottom images in the composite used the older CaKEBOS imagers, resulting in reduced resolution

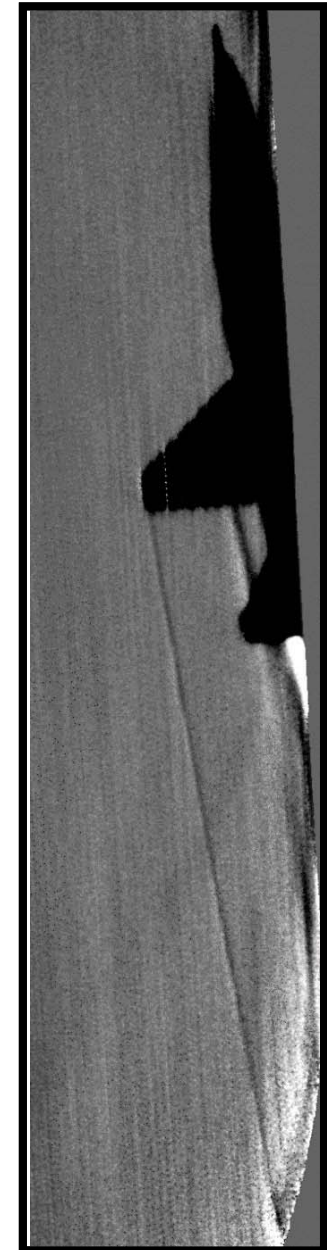
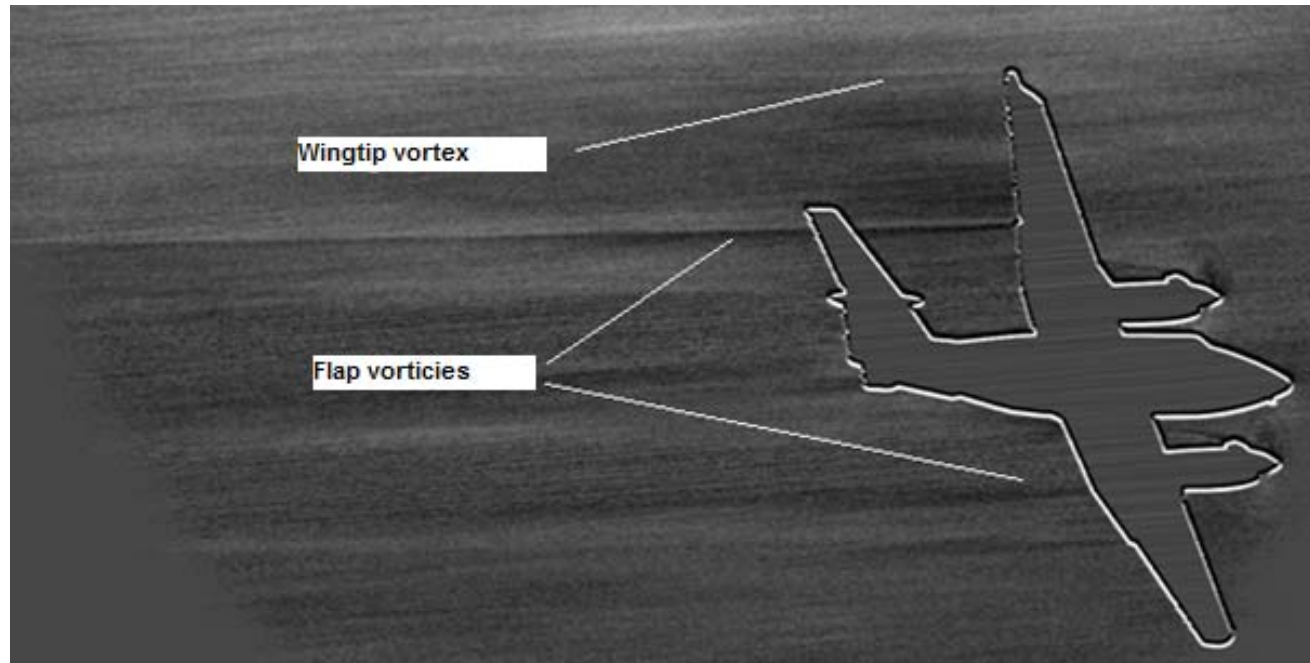


BOSCO – PHASE I: SUBSONIC RESULTS

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T-38 and Beech King Air eclipsing at 10,000ft AGL

- T-38 partially eclipsed the sun resulting in $\frac{1}{2}$ image
- A poor black level calibration on the camera during the King Air pass resulted in reduced quality raw data



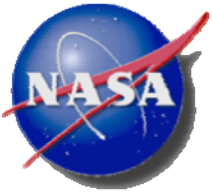


BOSCO- PHASE I: EXTENDED AFT VIEW

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- By processing many frames after the eclipse, flow features aft of the aircraft can be seen.
- Due to the short wingspan of the T-38, the image of the vortices are quickly Overwhelmed by the engine exhaust more than 5 body lengths aft





BOSCO – Phase II, April 2017

- Test of a new compact imaging system
- Closer range – 2 miles

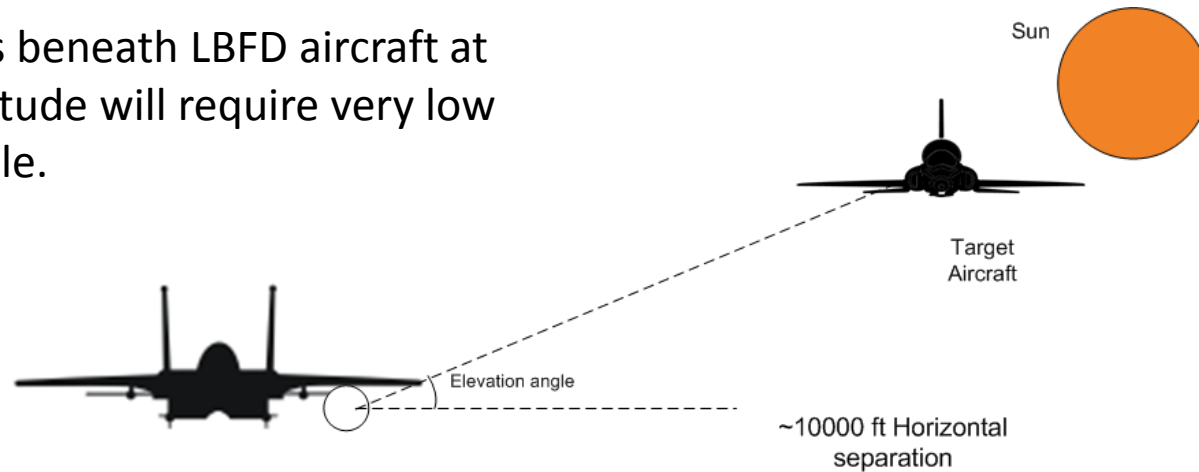




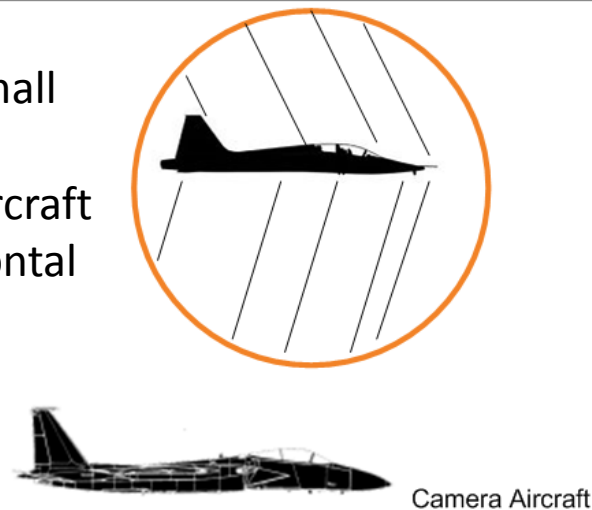
BOSCO – PHASE II MOTIVATION

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Imaging of shocks beneath LBFD aircraft at normal cruise altitude will require very low sun elevation angle.



Low elevation angles will require small differential altitude; future imaging system will be airborne. Camera aircraft will operate roughly 10,000ft horizontal separation from target

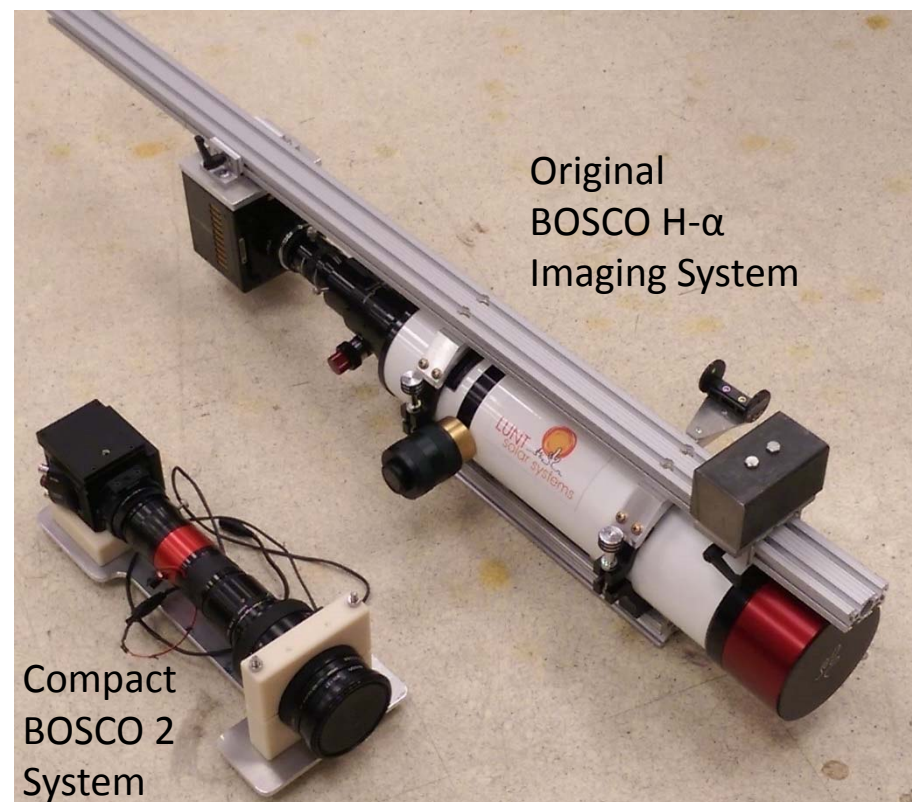
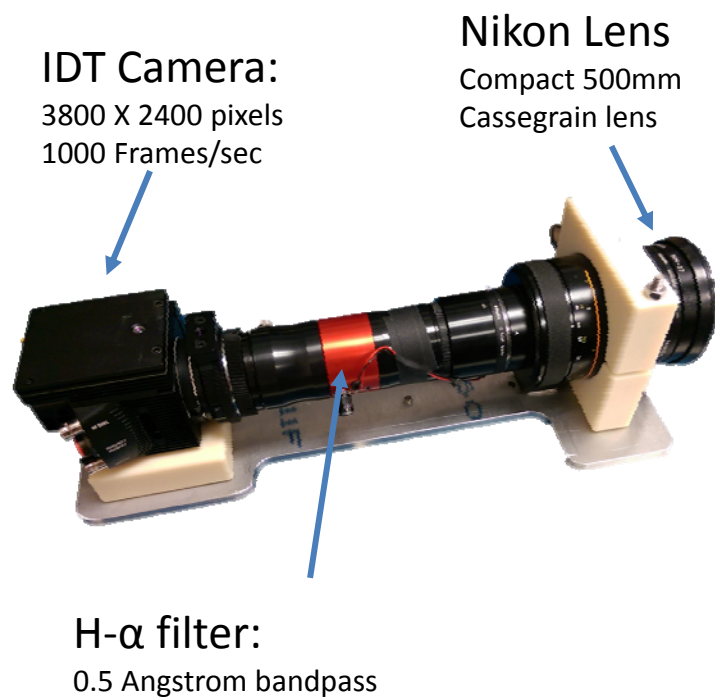




BOSCO – PHASE II

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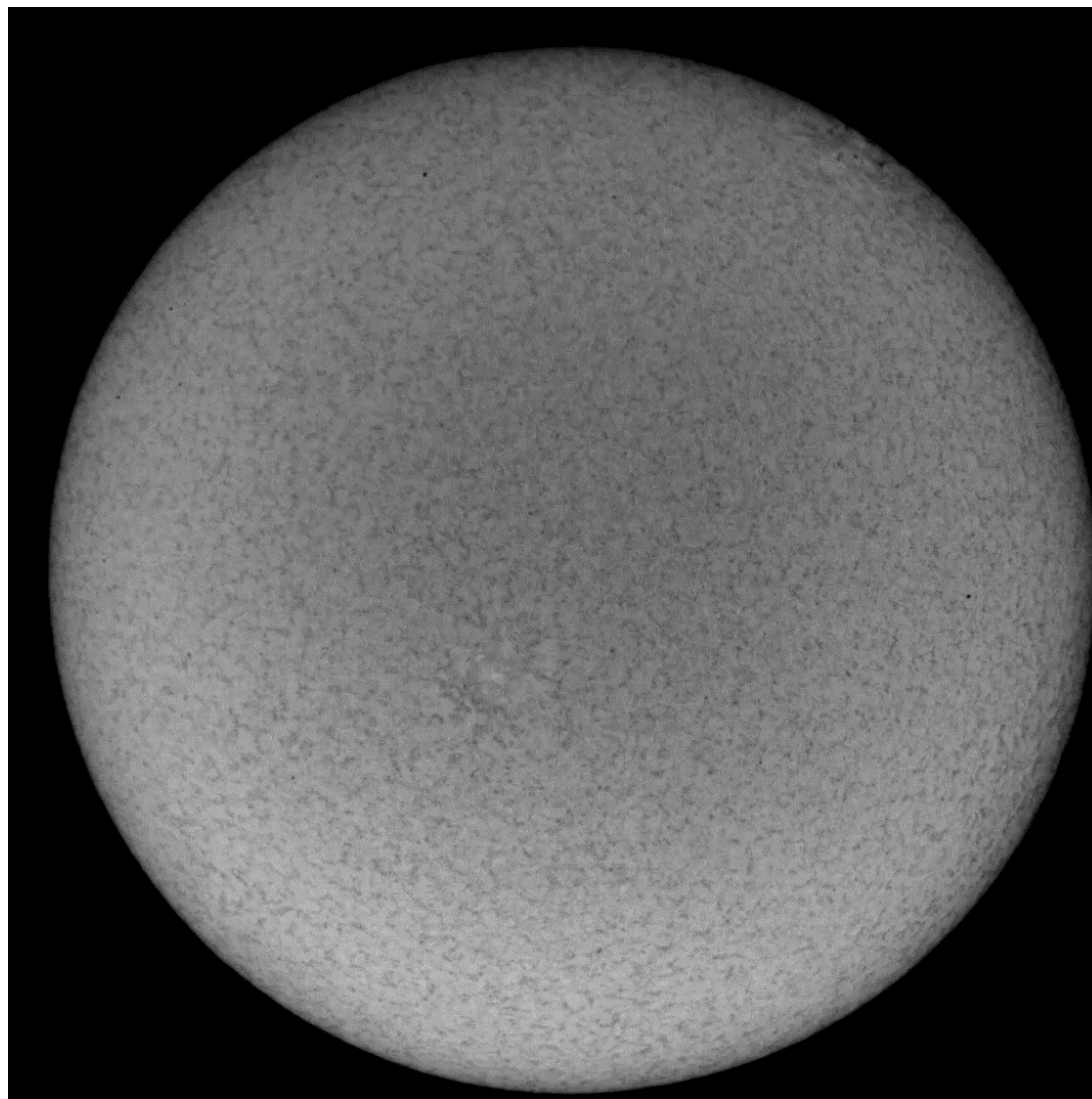
New compact imaging system for future airborne use





BOSCO – PHASE II RAW DATA

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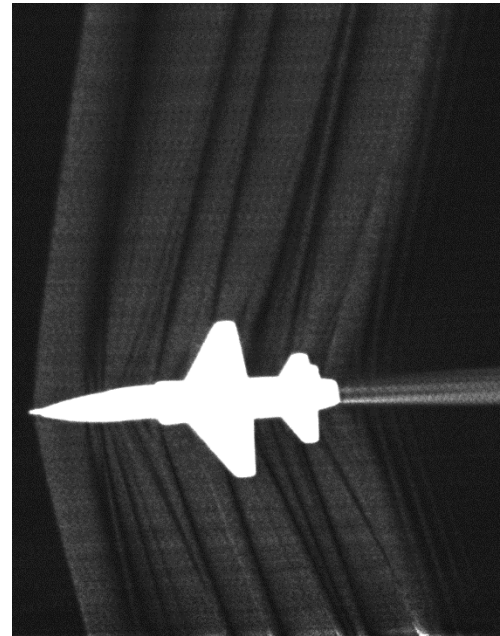




BOSCO – PHASE II RESULTS

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- Results
 - Images show much more shock detail at close range
 - The increase magnitude of background distortion at the closer range reduces the effectiveness of the optical flow image processing, resulting in noisier results
 - The reduced number of frames to de-noise with also increases noise in final images
 - Will not be an issue with airborne system
 - Compact imaging system performed satisfactory, but needs greater control over image focus

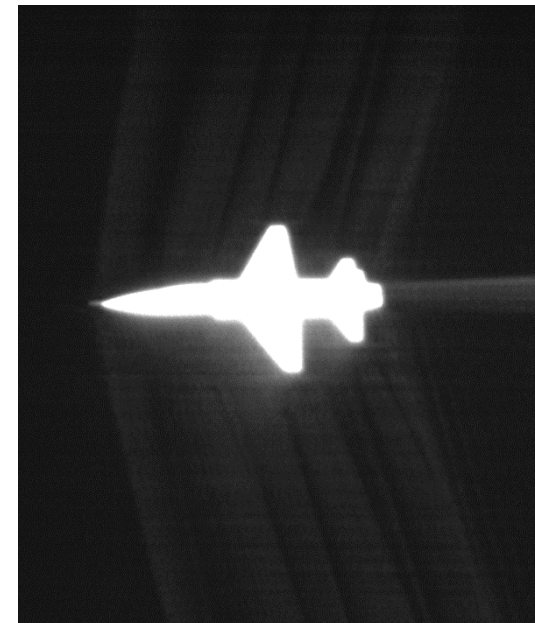


BOSCO- Phase I system

Single element,
fixed focal length
Primary lens

BOSCO- Phase II system

Multi element, compact
Cassegrain primary lens.
Oversensitive focusing
mechanism





CONCLUDING REMARKS AND FUTURE WORK

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- Solar chromosphere works well as a background for BOS
 - Both Hydrogen – α line and Calcium-K line produced good results.
 - H- α superior for BOS imaging
- Field of view can be increased with multiple camera array
- Extended view aft of the aircraft can be achieved by processing frames after the eclipse
- Subsonic flow features can be imaged
- Future work
 - Investigate alternate processing methods for close range images
 - Continue development of airborne imaging platform
 - Improve focusing mechanism on compact imager

